ESTCP
Cost and Performance Report

(WP-200924)

Demonstration of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid

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ESTCP

ENVIRONMENTAL SECURITY
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14. ABSTRACT
This report summarizes the findings from a full-scale side-by-side demonstration of Battelle Runway Deicing Fluid (RDF) versus conventional potassium-acetate (KAc) based RDF. The tests were conducted on a closed section of the Wright-Patterson Air Force Base runway using full-scale fluid application trailers. Anti-icing and deicing performance was based on runway friction rating, a measure of surface slipperiness, and holdover time. The two Battelle fluids tested met all acceptance criteria including lower aquatic toxicity (acute and chronic), similar oxygen demand, lower corrosion of aircraft components (cadmium-plated parts and carbon-carbon brake pads), and comparable runway friction and holdover times. A life-cycle cost analysis indicated that Battelle-RDFs were more cost effective than KAc-RDFs due to lower fluid cost and lower maintenance costs due to reduced metal corrosion and braking system damage.

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Runway deicing fluids; bio-based deicing fluids; aquatic toxicity; oxygen demand; runway surface friction; holdover time; life cycle costs

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ACRONYMS

ABW	Air Base Wing
AFB	Air Force Base
AFCESA	Air Force Civil Engineering Support Agency
AFI	Air Force Instruction
AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratory
AMS	Aerospace Materials Specification
ASC	Aeronautical System Center
ASM	Aircraft Single Manager
BOD	Biochemical Oxygen Demand
CDRL	Contract Data Requirements List
CRREL	Cold Regions Research and Engineering Laboratory
CFR	Code of Federal Regulations
COD	Chemical Oxygen Demand
CWA	Clean Water Act
DoD	Department of Defense
ENV	Environmental
EO	Executive Order
EPA	United States Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FAME	Fatty Acid Methyl Ester
FFA	Free fatty acids
FPD	Freezing point depressant
Gpy	gallons per year
GEN3	Trade name for Battelle-RDF sold by Basic Solutions LNT Group
GHG	Green house gas
HOT	Holdover time
IC_{25}	Inhibition concentration, calculated percentage of effluent at which the test organisms exhibit a 25% reduction in a biological function such as reproduction (as in the case of daphnids) or growth (as in the case of fish)
KAc	Potassium acetate
LC_{50}	Lethal concentration where 50% of organisms die
LCC	Life-cycle costs
LRB	Laboratory record book
MTMS	Military Test Method Standard
MTU	Michigan Technological University
NAAC	Sodium acetate (solid deicer)
NPDES	National Pollutant Discharge Elimination System
NSN	National stock number (also referred to as NATO stock number)
O_2	Oxygen
PG	Propylene glycol
PI	Principal Investigator
PNNL	Pacific Northwest National Laboratory
POC	Point of Contact

RCR	Runway condition rating
RDFs	Runway deicing fluids
SAE	Society of Automotive Engineers
SAIC	Science Applications International Corporation
S&ICP	Snow and Ice Control Plan
SERDP	Strategic Environmental Research and Development Program
SI	Sustainable Infrastructure
SMI	Scientific Materials International, Inc
USAF	United States Air Force
WP	Weapons Systems and Platforms
WPAFB	Wright-Patterson Air Force Base
WSSM	Weapon Systems Single Manager

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The project manager was Ms. Mary Wyderski. Technical and managerial contributions were provided by Dr. John Hall of the ESTCP program office.

The members of the project team (minus the authors) and their contributions are presented in Appendix A.

EXECUTIVE SUMMARY

BACKGROUND

Currently the Department of Defense (DoD) uses potassium acetate (KAc) based runway deicing fluids (RDFs) exclusively to deice and anti-ice military runways and taxiways. Commercial airports predominantly use KAc but some also use RDFs composed of KAc plus propylene glycol (PG) or urea plus PG. These RDFs have both environmental concerns due to toxicity as well as material compatibility problems due to corrosion of carbon brake-pad components and cadmium-plated landing gear and airfield lighting fixtures.

Under the SERDP project SI-1535, Battelle developed a series of effective bio-based RDFs to address these issues. Tests showed that the Battelle-RDFs met the mandatory Aerospace Material Specification 1435A specifications. It had reduced ecotoxicity and compliant with all other environmental requirements. And, it was found to be more compatible (i.e., less corrosive) to conventional aircraft and Air-Force unique materials (such as infrared windows, LO coatings, etc.). A full-scale demonstration was conducted with two Battelle-RDF formulations: 6-12 using a partially refined bio-based material and 6-3 using a fully purified bio-based material. These fluids were evaluated under anti-icing and deicing conditions on the runway at Wright-Patterson Air Force Base (WPAFB) during January and February 2010. Runway test sections 50-ft wide by 1,000-ft long were evaluated in side-by-side tests of the Battelle-RDF and Cryotech E36® KAc RDF. Two commercial Batts deicing-fluid delivery trailers were used. The tests produced sufficient data to allow statistically valid comparisons of the two Battelle-RDFs versus commercial KAc RDF.

OBJECTIVES OF THE DEMONSTRATION

The objective of the demonstration was to show that an advanced RDF prepared from low-cost bio-based raw materials was less toxic, less corrosive, and as effective as commercial KAc liquid RDFs in airfield deicing and anti-icing.

DEMONSTRATION RESULTS

The demonstration was a success. Prior to the testing, quantitative and qualitative performance objectives were established. The test results are summarized below:

- Quantitative
  - Environmental: 3 to 4 times less toxic
  - Oxygen demand: Intermediate between KAc RDF and KAc+PG RDF
  - Corrosion: 60 to 80% less corrosive to cadmium-plated landing gear and carbon-carbon brake pad components
  - Deicing and anti-icing performance: Comparable to KAc RDF
- Qualitative
  - Ease of use: Comparable to KAc RDFs
  - Maintenance requirements: Comparable to KAc RDFs.

The Battelle-RDFs were found to be suitable as a drop-in replacement for KAc RDF. A manufacturing analysis indicated that the Battelle-RDFs had lower fluid costs. A life cycle cost estimate indicated that the Battelle-RDFs had slightly higher wastewater treatment costs (due to slightly higher BOD levels). But, these increased costs were insignificant compared to the savings from lower airfield and aircraft maintenance costs (due to reduced Cd and carbon-carbon brake pad corrosion).

To quantify the savings across the DoD, it was estimated that the military (primarily the Air Force) consumes approximately 1 million gallons of RDF each year. Usage is spread over 31 active USAF bases, 45 Air National Guard Bases, and 4 Air Force Reserve Command bases located in the northern half of the U. S. along with bases in Japan and North Korea. This compares to an estimated 8 million gallons of KAc RDF used at U. S. commercial airports. It was estimated that if a "typical" Air Force Base (using 31k gallons of RDF/year) switched to Battelle-RDF, the savings would be ~$92k/year. The estimated savings grew to $2.9 million if the entire DoD switched, and $28 million if all DoD and commercial airports switched to Battelle-RDF.

IMPLEMENTATION ISSUES

Users may express concern because the Battelle-RDF is new and they may have reservations because of its potential damage to aircraft or weapon system components. These reservations should be allayed once the range of tests performed and the superior corrosion properties and comparable deicing/anti-icing performance of Battelle-RDFs are disseminated.

An important implementation issue is the manufacture and delivery of the RDF. Battelle is a research and development company and not an RDF vendor. This issue was resolved when Battelle licensed the technology to Basic Solutions North America Corporation. Basic Solutions distributes the Battelle-RDF 6-4 formulation under the trade name **GEN3 64™.** (Formulation 6-4 is similar to 6-12 and 6-3, except it has a higher bio-based content.) During the 2009/2010 deicing season, 15 Canadian commercial airports and 4 U. S. commercial concerns used or tested **GEN3**. In all these commercial airport trials, **GEN3 64™** was used without modification to the storage tanks, transfer pumps, deicing fluid trailers, spray nozzles, or fluid delivery pumps. This supports the conclusion that Battelle-RDFs can be readily implemented as a drop in replacement.

Prior to use in the Air Force and the DoD, the fluid was reviewed and accepted by the Air Force Civil Engineering Support Agency, the Air Force agency that provides guidance on allowable liquid and solid RDFs. Now that it has been accepted, the Aircraft Single Managers (ASMs) and Weapons System Single Managers (WSSMs) can be notified that **GEN3** is approved for use. A National Stock Number (NSN) may be requested and secured to facilitate procurement. Finally, and most importantly, the ASMs and WSSMs will have to review the environmental, material compatibility, and performance data and accept **GEN3** for use on their aircraft and/or weapon system. In some cases, special material-compatibility concerns may delay acceptance; or additional material-specific testing may be required by a weapon system before acceptance.

1.0 INTRODUCTION

This Cost and Performance Report is organized per the ESTCP Guidance for Sustainable Infrastructure (SI) Facilities and Energy projects. It consists of the following nine sections and one Appendix:

1. Introduction
2. Technology Description
3. Performance Objectives
4. Site Description
5. Test Design
6. Performance Assessment
7. Cost Assessment
8. Implementation Issues
9. References.

Appendix A: Points of Contact.

This report is a condensed version of the Final Report [1].

1.1 BACKGROUND

Currently the DoD uses potassium acetate (KAc) based runway deicing fluids (RDFs) exclusively for their liquid pavement deicing needs to deice and anti-ice military runways and taxiways. Commercial airports predominantly use KAc but some also use RDFs composed of KAc plus propylene glycol (PG) or urea plus PG.

The DoD faces a significant environmental and military readiness problem due to the use of aqueous solutions of the KAc RDF. Originally the airports used urea or PG for runway deicing; however, due to the high biochemical oxygen demand (BOD) and high chemical oxygen demand (COD) of urea and PG, as well as the high ecotoxicity of urea, the DoD and most US commercial airports have switched to organic salts such as KAc. Studies now indicate that the acetate and formate deicers are more toxic than originally recognized [2].

While the acetate and formate deicers have a much lower BOD and COD than urea or PG, they are corrosive to aircraft components leading to military readiness problems. Recent testing by AFRL indicates their compatibility with advanced DoD aircraft is questionable [3]. In recent Society of Automotive Engineers (SAE) G-12 Aircraft Ground Deicing Fluids Subcommittee meetings, there has been serious concern expressed about the more commonly used KAc and formate deicers because of the corrosion of very expensive carbon-carbon brake pads and associated components, as well as landing gear components containing cadmium (Cd).

These concerns are likely to lead to the use of larger quantities of toxic corrosion-inhibitors and/or the use of less corrosive but high-BOD/COD alternatives, such as PG or PG + acetate mixtures. Therefore, both the environmental and material compatibility concerns are currently threatening the runway maintenance and aircraft availability for both the DoD and commercial sectors.

As documented in the Strategic Environmental Research and Development Program (SERDP) project SI-1535 final report, a series of effective RDFs were developed to address these environmental and material compatibility issues [4]. A multi-tiered approach was used to formulate RDFs with the ultimate objective of passing the mandatory Aerospace Material Specification (AMS) 1435A specifications as well as meeting or exceeding other key environmental, materials compatibility, and deicing performance requirements. The key to simultaneously improving the properties of and reducing the cost of RDF was to use low-cost, bio-based ingredients as a substitute freezing point depressant (FPD). Use of bio-based FPD along with KAc and food-grade additives allowed the production of an environmentally friendly RDF that is more compatible with runway/pavement and aircraft components, meets all performance requirements, and costs less.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of these tests is to demonstrate that an advanced RDF prepared from low-cost bio-based raw materials is less toxic, less corrosive, and as effective as commercial KAc liquid RDFs in airfield anti-icing and deicing at WPAFB.

1.3 REGULATORY DRIVERS

There are several drivers for implementing a new, more environmentally friendly RDF.

1.3.1 Water Pollution Reduction

The Clean Water Act (CWA) and its National Pollutant Discharge Elimination System (NPDES) (40 CFR 122.26) requires facilities that discharge point-source storm water to obtain an NPDES permit. All the RDF used for deicing/anti-icing the runways and apron ways enters the airfield water drainage system. The US EPA requested industry comments on new effluent limitations guidelines in August 2009 [5]. This proposed guideline addressed wastewater collection practices used by airports, and the EPA proposed a ban on the use of urea for runway deicing. However, there is likely to be pressure in the future to control the toxicity of RDFs.

1.3.2 Greening of the DoD

The following three Executive Orders (EOs) dictate that federal agencies promote the increased use of bio-based materials:

1. EO 13134 “Developing and Promoting Biobased Products and Bioenergy,” President Clinton, 1999.
2. EO 13423 “Strengthening Federal Environmental, Energy, and Transportation Management,” President Bush, 2007.
3. EO 13514 “Federal Leadership in Environmental, Energy, and Economic Performance,” President Obama, 2009.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

2.1.1 Technology Description

Battelle's proprietary formulations and associated processes include applications for runway and pavement deicing [6-9]. The Battelle-RDFs are based on a novel chemistry. Battelle's proprietary process (covered by U.S. Patent 7,048,871) is based on altering the tail-end of the process for making fatty acid methyl ester (FAME) by transesterification of triglycerides typically derived from vegetable oil seeds or other fats [10]. While there is a well-established oleochemical industry based on this process, the use of FAME as biodiesel is rapidly growing. By altering the transesterification (FAME/biodiesel production) process, Battelle has been able to make RDF formulations that address the current aircraft corrosion problems while providing environmental and cost benefits.

A typical process for making FAME (also used as biodiesel) is as follows:

$$\text{Triglycerides (fats/oils)} + \text{Methanol} \xrightarrow[\text{Catalyst}]{\text{NaOH}} \text{Fatty Acid Methyl Ester} + \text{Work By-product}$$

A simple, atmospheric pressure process yields about 90% FAME. The spent sodium hydroxide (NaOH) catalyst is typically neutralized with hydrochloric acid (HCl) resulting in a side stream containing waste by-products, sodium chloride (NaCl) salt, methanol, water, and some free fatty acids (FFA). Currently, this by-product is only used after refining it into pure components by eliminating all impurities through an expensive, multi-step process and rejecting most impurities as hazardous waste. This side stream is typically unsuitable for making an RDF due to the presence of NaCl, FFAs, and color forming and odor emitting impurities.

In Battelle's process, the HCl acid is replaced with a suitable organic acid that not only neutralizes the NaOH, but also forms an effective deicing salt (e.g., an acetate or a formate salt) along with the bio-based FPD [10]. Furthermore, a simple process, based on a proprietary Battelle process, can be used to remove FFA and other organic impurities that cause slipperiness and impart objectionable color and odor, while retaining all of the deicing chemicals (bio-based FPD and sodium acetate/formate). Since these by-products from FAME/biodiesel production provides for a maximum of 8% organic salt, it is beneficial to add an additional organic salt to obtain improved deicing properties as well as to reduce BOD/COD. Because of the non-corrosive (actually corrosion inhibition) nature of bio-based ingredients such as the biodiesel by-product, an RDF is formulated without the need for exotic corrosion inhibitors. In this manner, an alternative RDF is made at a significantly lower cost than formulations made from pure components and other additives.

A total of six RDFs were thus formulated and fully certified under AMS 1435A under the SERDP program; details of the RDFs of primary interest to the DoD are provided in Table 1.

Table 1. Description of Selected Certified Battelle-RDF Formulations

No.	Battelle-RDF Designation	Bio-based Freezing Point Depressant Purification	Secondary FPD	Applications
1	6-12	Low-cost purification for RDF-specific use	KAc	Deicing and anti-icing
2	6-2	Conventional; very high purity	KAc	Deicing and anti-icing
3	6-3	Conventional; very high purity	KAc	Deicing and anti-icing
4	6-4	Conventional; very high purity	KAc	Deicing and anti-icing

These formulations provide a range of chemical compositions that allow a user to select the desired environmental and materials property improvements as well as cost reductions. The two preferred RDFs were selected from this set:

- RDF 6-12: made from biodiesel by-products using a low-cost Battelle-developed purification process.
- RDF 6-3: made from highly purified biodiesel by-products.

These two formulations were selected because:

1. They were the most cost-effective formulations.
2. The represented two levels of biodiesel upgrading (minimal and full purification).
3. Both RDFs passed the Air Force's Military Test Method Specification (MTMS) Tier-3 tests.

A brief summary of the properties of two selected formulations and alternative liquid RDFs are provided in Table 2. Note: Much of the data was collected during SERDP project SI-1535 and is included as part of the performance findings discussed in a later section.

Table 2. Comparison of Two Battelle-RDF Formulations versus Commercial Alternatives

Parameter	RDF Designations			
	Battelle-RDF 6-12	Battelle-RDF 6-3	KAc	KAc+PG
BOD_5, kg O_2/kg fluid	Intermediate	Intermediate	Slightly lower	Highest
COD, kg O_2/kg fluid	Intermediate	Intermediate	Slightly lower	Highest
Acute toxicity	Lower	Lowest	Medium	Medium
Chronic toxicity	Lowest	Lower	Medium	Medium
Ice melting time, min	Comparable to KAc	Comparable to KAc	Comparable to KAc	Comparable to KAc
Friction	Comparable to KAc	Comparable to KAc	Not applicable	Slightly inferior to KAc
Brake pad life	Longer	Longest	Shortest	Intermediate
Life cycle cost vs. KAc	Lowest	Lower	Highest	Higher

2.1.2 Overall Schematics

Figure 1 contains a flowsheet for making Battelle-RDF from biodiesel by-products.

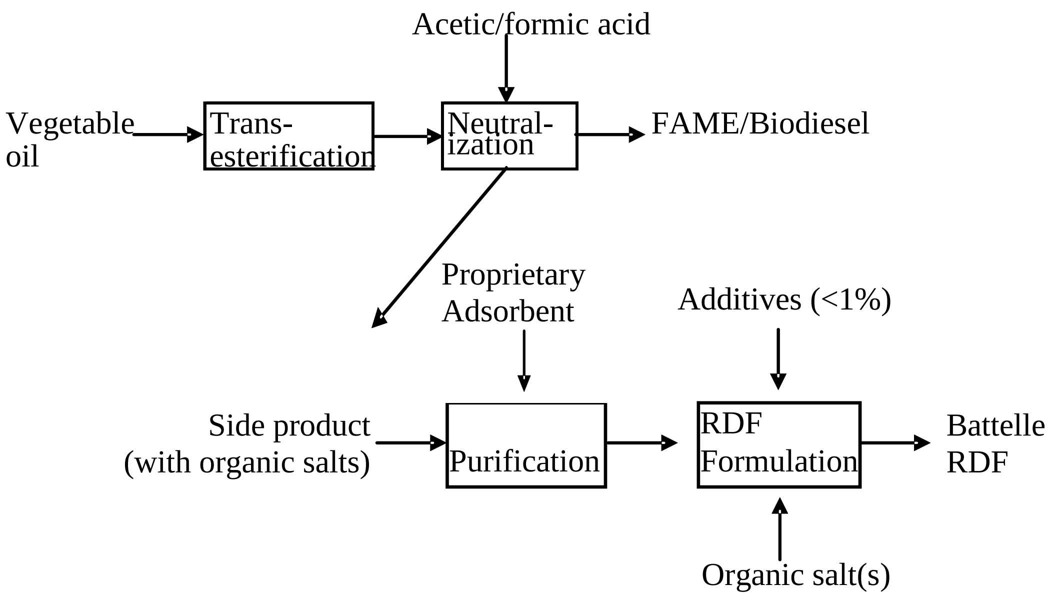

Figure 1. Battelle-RDF Process

2.1.3 Chronology

For the past nine years, staff members from Battelle and the Battelle-managed Pacific Northwest National Laboratory (PNNL) have been developing a variety of deicing/anti-icing fluids derived from renewable (bio-based) resources. Three patents were obtained in the 2006 – 2007 timeframe. In 2007, Battelle and PNNL began a SERDP project to optimize an RDF formulation.

2.1.4 Expected Applications

It is expected that the Battelle-RDFs can be used interchangeably with liquid KAc and/or KAc+PG RDFs, i.e., serve as a drop in replacement for military or civilian liquid runway deicing and anti-icing fluids. The two Battelle-RDF fluids have very similar environmental, physical, corrosion, and performance properties, so it is expected that either formulation could be selected. Of course, RDF 6-12 is anticipated to cost less, and would be the preferred formulation. However, RDF 6-12 can only be prepared where formulators have access to biodiesel waste by-product produced using acetic acid as the neutralizing agent in the biodiesel operation. Other acids, such as HCl or sulfuric acid are frequently cheaper and, therefore, are more commonly used in biodiesel production, so not every biodiesel plant will generate acetate crude. Battelle-RDF 6-3 will be used when only pure compounds are available.

2.2 TECHNOLOGY DEVELOPMENT

The Battelle-RDF technology was developed under a Battelle funded internal research and development program and was subsequently laboratory tested under the SERDP project entitled "Development of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid," SI-1535 [4].

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Advantages and Limitations

The advantages and limitations of the Battelle-RDFs and KAc RDF are noted below:

- Advantages: Lower ecotoxicity, better corrosion properties, and lower life cycle costs.
- Comparables: Deicing, anti-icing, hold-over time, and friction properties.
- Limitations: Slightly higher BOD/COD.

2.3.1.1 Advantage – Lower Toxicity. The acute and chronic ecotoxicity of both Battelle-RDFs were less than half that of currently used RDFs.

2.3.1.2 Advantage – Cadmium Corrosion. The Battelle-RDFs were typically 75% to 80% less corrosive than currently used RDFs.

2.3.1.3 Advantage – Brake Component Corrosion. The Battelle-RDFs were typically 61 to 78% less reactive to carbon, and are thus projected to improve brake life from one year (current life) to 2.6 to 3.6 years [11].

2.3.1.4 Advantage – Economics. A cost-benefit analysis described in Section 7 of this report showed that the Battelle-RDFs were not only cheaper than KAc or KAc+PG RDF alternatives, but also offer reduced aircraft/airport maintenance costs for a lower life-cycle cost.

2.3.1.5 Comparable – Ice Melting and Anti-icing Performance. The full-scale demonstration on the WPAFB runway confirmed the results from Michigan Technological University (MTU) showing comparable ice melting, ice undercutting, and ice penetration performance [4]. The MTU tests were conducted in accordance with the *Handbook of Test Methods for Evaluating Chemical Deicers* [12].

2.3.1.6 Comparable – Friction. The full-scale demonstration confirmed the Battelle-RDFs are as good as KAc RDFs in terms of friction. These results matched the Federal Aviation Administration (FAA) runway friction test findings.

2.3.1.7 Disadvantage – Higher Oxygen Demand. U.S. airports are currently using KAc-based RDFs but are considering a move towards using mixtures of KAc and PG to reduce the corrosion of aircraft materials. The BOD/COD of the two Battelle-RDFs selected for the demonstration have oxygen demands that were slightly higher than KAc but lower than KAc+PG RDFs.

3.0 PERFORMANCE OBJECTIVES

Battelle-RDFs represent viable alternative RDFs, i.e., they can serve as an improved drop-in replacement for organic-salt based RDFs like KAc. Table 3 shows that each acceptance criterion was met.

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Table 3. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Environmental				
Safeguard waterways by lowering acute toxicity	LC_{50}, mg/L, water fleas (*Daphnia magna*, 48 hr)	Data on acute and chronic toxicity	LC_{50} higher than for KAc RDF (>1,000 mg/L)	Success
	LC_{50}, mg/L, fathead minnows (*Pimephales promelas*, 96 hr)		LC_{50} higher than KAc RDF (>1,000 mg/L)	Success
Safeguard waterways by lowering chronic toxicity	IC_{25}, mg/L, Ceriodaphnia magna		IC_{25} higher than KAc RDF (>800 mg/L)	Success
	IC_{25}, mg/L, Pimephales promelas		IC_{25} higher than KAc RDF (>300 mg/L)	Success
Safeguard waterways by controlling oxidative load	COD, kg O_2/kg RDF fluid	Wastewater treatment load and surcharge costs need for the life-cycle cost analysis	COD falls between KAc and KAc+PG RDF levels (i.e., between 0.3 and 0.73 kg O_2/kg RDF fluid)[a]	Success
	BOD_5, kg O_2/kg RDF fluid		Values fall between KAc and KAc+PG RDF levels (between 0.15 and 0.32 mg/L)[a]	Success
Corrosion of cadmium-plated parts				
Maintain life of Cd-plated landing gear and aircraft lighting components to ensure safe, extended operation	Weight change, mg/cm^2/24 hr	Data to estimate landing-gear component life needed for life-cycle cost analysis	Lower weight change, as determined by the AMS 1435A cadmium-corrosion test, when compared to KAc RDF	Success
Corrosion of carbon-carbon brake pads				
Maintain life of brake pads to ensure safe and extended operation	Weight loss, %	Data to estimate brake pad life needed for life-cycle cost analysis	Lower weight loss, as determined by the Honeywell brake pad protocol, when compared to KAc RDF	Success
Performance – during anti-icing (RDF dosage ~0.5 gal/ 1000 ft^2) [a]				
Maximize the amount of time runways and taxiways are maintained snow- and ice-free	Holdover time (HOT), minutes	Time the surface remains suitable for aircraft operation	Comparable or longer HOT, compared to KAc RDF	Success

[a] If the Battelle RDF COD or BOD5 levels were at or below the KAc RDF levels, that would also be considered a "success."

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Maintain sufficient runway and taxiway friction values to ensure safe landings and taxing,	Friction coefficient expressed in terms of Runway Condition Rating (RCR)	Pavement surface friction data	Comparable or higher rating compared to KAc, RCR	Success
Performance – during deicing (RDF dosage ~2 gal/1000 ft^2) [(a)]				
Reduce time to prepare runways and taxiways for operation	Melting efficiency, minutes	Melting times, used to estimate relative fluid dosage requirements needed for life-cycle cost estimate	Comparable or shorter ice-melting times, compared to KAc-RDF	Success
Maintain sufficient runway and taxiway friction values to ensure safe landings and taxiing	RCR	Pavement surface friction	Comparable or higher rating, compare to KAc RDF	Success
Qualitative Performance Objectives [(b)]				
Ease of use	Ability of RDF operator to use the fluid as a drop-in replacement for KAc; expressed on a scale of 1 to 10	Feedback from operators on usability of the Battelle-RDF, including filling, fluid application, smell, etc.	Based on user surveys, achieve an equal or superior rating compared to KAc RDF (based on a minimum of two WPAFB RDF users and the Operations Chief's assessment of usability)	Success
Maintenance	Ease of maintenance; expressed on a scale of 1 to 10	Feedback from operators on ability to maintain runway deicing equipment when using Battelle-RDF, lack of corrosion or required modifications	Based on user surveys, achieve an equal or superior rating compared to KAc RDF (based on a minimum of two WPAFB RDF users and the Operations Chief's assessment of maintenance issues)	Success

(a) The quantitative assessment for anti-icing (hold-over time and RCR) and de-icing (melt time and RCR) was compared for the three RDFs. The estimated mean for each RDF, corrected for time of day effects, and estimated 95% confidence interval, again corrected for time of day effects, of the three RDFs during anti-icing and deicing tests was determined. If the Battelle-RDFs' confidence interval exceeded the KAc confidence interval, the fluid was considered superior; if the two intervals overlapped, then the fluid was classified as comparable. If the KAc interval exceeded the Battelle-RDF interval, with no overlap, the Battelle-RDF was considered inferior. An example is provided later in the text.

(b) The quantitative performance measures for ease of use and maintenance was compared for the three RDFs. KAc performance ratings were assessed by the observers and an average was calculated. Comparable data for the Battelle-RDFs were tallied. If the Battelle-RDFs' average values fell within the KAc RDF value ± two digits, then the Battelle-RDF was considered to have comparable performance.

4.0 FACILITY/SITE DESCRIPTION

WPAFB was chosen for this demonstration for four reasons:

1. Weather: Winter weather at the base had cold temperatures with adequate snow and icy precipitation.
2. Facilities: Suitable test runways, deicing equipment, and trained RDF technicians were available.
3. Operations staff: Airfield operations crews that were enthusiastic about participating in the demonstration were available.
4. Air Force deicing expertise: WPAFB houses staff members from the ASC and AFRL, who have the Air Force responsibility to advise on aircraft and runway deicing technologies and operations.

4.1 FACILITY /SITE LOCATION AND OPERATIONS

WPAFB is located in Greene and Montgomery counties, eight miles northeast of the central business district of Dayton, Ohio, United States. It is the headquarters of the Air Force Materiel Command, one of the major commands of the Air Force. WPAFB is also the location of a major USAF Medical Center (hospital), the Air Force Institute of Technology, and the National Museum of the United States Air Force.

It is also the home base of the 445th Airlift Wing of the Air Force Reserve Command, an Air Mobility Command unit that flies the C-5 Galaxy heavy airlifter. WPAFB is also the headquarters of the Aeronautical Systems Center (ASC) and the AFRL [13]. From the 2008 Base Economic Impact Analysis, WPAFB has a total of 25,713 military, civilian, and contractor employees [14].

WPAFB has two major runways; Figure 2 is a photo of the airfield circa 2000. These runways support all types of aircraft from C-5 Galaxy heavy cargo aircraft to commercial Boeing 747s. The long runway is made of concrete and is 12,000-ft long by 300-ft wide. The short runway consists of an asphalt overlay and is 7,000 ft by 150-ft wide. Testing sites were available on the 2,600-ft out-of-service portion of the long runway. No aircraft were used in the testing as this was not required for successful demonstration.

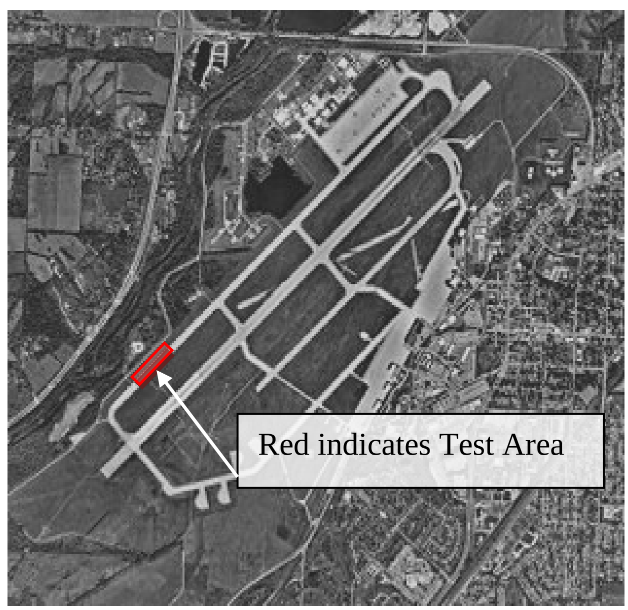

Figure 2. WPAFB Airfield Showing Sites for Demonstration Testing [13]

Currently the airfield uses two types of runway deicers, liquid KAc and solid sodium acetate (NAAC). During the fall 2007 to Spring 2008 deicing season, 14,200 gal of KAc and 90 metric tons of NAAC were used. Battelle-RDF was transferred from the 250-gallon shipment totes into one of WPAFB's RDF spray tankers for the demonstration.

Testing was performed at WP-AFB following Air Force Instruction (AFI) 32-1002 "Snow and Ice Removal," [15]. It stipulated that installations with over 6 inches average annual snowfall maintain a Snow and Ice Control Plan (S&ICP) and form a Snow and Ice Control Committee. The S&ICP is tailored to meet local needs. It includes snowfall history, equipment and attachment inventory, equipment plowing patterns, team composition, materials and parts levels, and color-coded maps [16].

4.2 FACILITY SITE CONDITIONS

The weather in the Dayton area, and nearby WPAFB, in January and February is cold (lows range from 18 to 24ºF). The base also typically receives several inches of snow as noted in Table 4.

Table 4. 2008/2009 Snowfall at WPAFB

[17]

Winter Season, Start and End Year	WPAFB Snowfall, Monthly Value, inch [(a)]				
	Nov	Dec	Jan	Feb	Mar
2000-2001	0.1	9.3	1.5	2.0	0.8
2001-2002	0.0	1.8	4.5	1.5	1.9
2002-2003	1.8	4.6	10.1	15.7	0.3
2003-2004	0.0	2.9	3.2	0.9	7.0
2004-2005	0.0	14.9	4.6	2.5	1.2
2005-2006	1.7	7.6	0.4	1.2	3.0
2006-2007	0.0	0.0	2.8	8.5	0.0
2007-2008	0.0	6.1	1.3	9.1	14.0
2008-2009	0.0	0.0	13.8	0.4	0.0

(a) These figures depict snowfall levels and do not reflect rain or freezing rain requiring snow and ice control actions.

These conditions were suitable for an RDF demonstration. Conditions requiring both deicing and anti-icing were encountered during the demonstration period.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

On a series of cold, wintery days in the winter of 2010, when temperatures were below freezing, water was applied to simulate ice storm conditions. Two WPAFB liquid deicing trucks spread the test RDFs across the parallel test areas. Anti-icing and deicing performance data were collected. Results for the Battelle-RDFs were compared to the performance of commercial liquid KAc runway deicing fluid (the RDF currently used at the base) under similar snow/ice/temperature conditions to access relative effectiveness.

5.2. BASELINE CHARACTERIZATION

Tests followed AFI 32-1002 "Snow and Ice Control," and more specifically the WPAFB snow and ice control plan (S&ICP). The AFI provided guidance on the type of deicing chemical to be used and dosage rates (i.e., gal of liquid deicer per thousand square feet) as a function of operation (deicing versus anti-icing) and ice thickness. The anti-icing dosage was ~0.5 gal/1000 ft^2. Deicing dosage depended on both ice depth and temperature, but was typically 2 gal/1000 ft^2. However, to provide an exact comparison on anti-icing and deicing effectiveness, side-by-side tests of Battelle-RDF and KAc RDF were conducted for anti-icing, using the prescribed RDF dosage. For deicing, testing were conducted using constant deicer dosage rates.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 Demonstration Set-Up

Prior to arriving at WPAFB, Battelle-RDFs 6-12 (1,000 gal) and 6-3 (3,000 gal) were manufactured by a toll producer under the supervision of Battelle. The commercial KAc RDF (E36 manufactured by Cryotech) used at WPAFB was supplied by the ABW for comparison testing.

5.3.2 Amount of Material Tested

4,000 gal of the two Battelle-RDFs were manufactured for the demonstration. Approximately 500 gal of each RDF was used in the anti-icing and deicing demonstrations.

5.3.3 Operating Parameters for the Technology

The test objective was to demonstrate that Battelle-RDFs 6-12 and 6-3 were as effective as commercial KAc RDFs in airfield anti-icing and deicing. Quantitative data and qualitative observations were collected to establish that the RDFs were as effective, were as easy to use, and had similar maintenance requirements.

5.3.4 Experimental Design

Prior to proceeding with the demonstration at WPAFB both Battelle-RDFs passed all AMS 1435A certification testing. A "Fluid Qualification Report" was supplied to the base to document successful completion of all requirements [18].

The demonstration used Battelle-RDF 6-12 and 6-3 on the closed section of the long runway. To verify the laboratory runway anti-icing and deicing performance, a demonstration procedure used in prior full-scale RDF testing procedure developed by Battelle and Basic Solutions (an RDF vendor) was employed. The two Battelle fluids were evaluated for (a) anti-icing and (b) deicing at WPAFB. Two RDF fluid distribution "Batts Deicer Pro Series" trucks were used. Each was filled with 500 gal of RDF.

5.4 OPERATIONAL TESTING

A single 1-week field trial was originally planned to conduct the field tests at WPAFB. However, due to the weather, the anti-icing tests were conducted in January and the deicing tests in late January and February 2010. Table 5 notes the time periods when the on-site WPAFB demonstration tests were conducted.

Table 5. Test Periods

Demonstration Efforts	Time Period (2010)
Anti-Icing	
6-3 vs. KAc	12 January
6-12 vs. KAc	13 January
Deicing	
6-3 vs. KAc	29 January
6-12 vs. KAc	26 February

The results were used in the assessment of life-cycle cost for deploying the bio-based RDF for military applications. The results are described in Section 7 of this report.

5.5 SAMPLING PROTOCOL

The two Battelle-RDFs were sampled after production and analyzed for specific gravity and pH per AMS 1435A to make sure the formulations were correct.

Anti-icing and deicing performance data were collected during the WPAFB demonstration testing. During the on-runway tests, data such as date, time, meteorological conditions, and application information were collected. This is described in greater detail in the Final Report [1]. The protocol for extracting the quantitative performance data, including ice melting time, friction, and holdover time are noted in Table 6.

Table 6. Quantitative Data Collection Protocol

Test Type	Parameter	Parameter Description	Test Preparation	Collection Protocol
Anti-Icing	Holdover Time (HOT)	Time surface remains suitable for aircraft landing	On two adjacent section of runway, apply Battelle-RDF and KAc RDF during simulated ice storm (by applying water spray to the below freezing runway surface).	Collect RCR data using a de-accelerometer Calculate HOT as the time from start of water application to time RCR falls below acceptable limits.
	Runway Condition Rating (RCR)	Measure of runway friction/suitability for landing		Collect RCR data.
Deicing	Melt time	Time to melt the ice to create an acceptable runway surface	On two adjacent sections of runway, apply water spray to make uniform iced runways. Apply Battelle-RDF and KAc RDF	Collect RCR data. Calculate melt time as the time required to transform the iced runway into one suitable for landing (based on RCR)
	RCR	Measure of runway friction/suitability for landing		Collect RCR data. Compare RCR data for the two RDFs

Qualitative data on ease of use and maintenance were also collected via survey of test observers and staff of the 88th ABW.

5.6 SAMPLING RESULTS

The sampling results included testing for acute and chronic toxicity, oxygen demand, Cd corrosivity, and carbon-carbon brake pad oxidation were obtained from the prior SERDP project [4]. The results are shown in Tables 7 though 11.

The RDF samples were analyzed by SMI Inc., as part of the AMS 1435A certification executed during the SERDP project, for acute ecotoxicity. As noted in Table 7, the LC_{50} concentration, the highest concentration in mg/L at which 50% of the test species die, was determined for two species. The higher LC_{50} values indicate that Battelle-RDFs are 3 to 4 times less toxic compared to the KAc-RDF.

As noted in Table 8, Battelle-RDFs 6-12 and 6-3 were evaluated for chronic toxicity. The higher IC_{25} values for the two Battelle-RDFs, compared to the KAc-RDF, indicate that the Battelle-RDFs have lower chronic toxicities.

The RDF samples were analyzed for COD and BOD_5 by SMI Inc., as part of the AMS 1435A certification executed during the SERDP project. Results are shown in Table 9. The values for the two Battelle-RDFs fall between KAc-RDF and KAc+PG RDF, which indicate that these RDFs have intermediate demands.

Table 7. Acute Toxicity Results

Sample	*Daphnia magna* (water flea) 48-hr LC_{50}, mg/L	*Pimephales promelas* (fathead minnows) 96-hr LC_{50}, mg/L
Commercial Acetate RDF	1,000 (Typical)	1,000 (Typical)
RDF 6-12	3,275	4,325
RDF 6-3	4,025	4,425

Table 8. Chronic Toxicity Results

RDF	*C. dubia* IC_{25}, mg/L	*Pimephales promelas* IC_{25}, mg/L
Commercial RDF #1	828	283
Commercial RDF #2	406	189
Battelle-RDF 6-3	1,100	2,400
Battelle-RDF 6-12	2,600	2,000

Table 9. Chemical and Biochemical Oxygen Demand Results

Sample	COD kg O_2/kg	BOD_5 @ 20°C kg O_2/kg
Commercial KAc RDF	0.30 (Typical)	0.15 (Typical)
Commercial KAc+PG RDF	0.73 [(a)]	0.32 [(a)]
RDF 6-12	0.50	0.26
RDF 6-3	0.52	0.30

(a) From technical specification for Octagon Process's Octamelt (a KAc+PG RDF).

The RDF samples were analyzed for Cd corrosion by SMI Inc., as part of the AMS 1435A certification executed during the SERDP project. The results are shown in Table 10. Corrosion rates were 61% lower for RDF 6-12 and 78% lower for RDF 6-3 compared to KAc RDF.

Table 10. Cadmium Corrosion Results

Sample	Cd Corrosion Rate, Wt. Change, mg/cm^2/24 hours [(a)]
Commercial KAc RDF	0.16
RDF 6-12	0.03
RDF 6-3	0.04

(a) Specification limit: < 0.3.

RDF-induced brake-component corrosion is a serious problem. The SAE Subcommittees A-5A (for aircraft brakes) and G-12 (for deicing fluids) have developed methods to analyze corrosion data in order to predict the propensity for catalytic oxidation of carbon brakes by RDFs. Details are provided in the Final Report [1]. Comparative normalized results obtained during the SERDP project are shown in Table 11. Both test methods confirm that Battelle-RDFs had 60% (for RDF 6-12) to 80% lower (for RDF 6-3) catalytic oxidation activity compared to KAc RDF. This could extend brake life from 1 year (current) to 4 years between replacements.

Table 11. Carbon Pad Loss Results

Sample	Weight Loss, % Meggitt, 50% Conc., 550ºC	Weight Loss, % Honeywell, 100% Conc., 650ºC
Commercial KAc RDF	18	32
RDF 6-12	7	12
RDF 6-3	4	9

A comparison of anti-icing performance is provided in Tables 12 and 13.

Table 12. Comparison of Anti-Icing Friction Values

	RCR: Anti-Icing Series No. 1 (Confidence interval at 36 min. elapsed time)			RCR: Anti-Icing Series No. 2 (Confidence interval at 23 min. elapsed time)		
Parameter	RDF 6-3	KAc RDF	Assessment	RDF 6-12	KAc RDF	Assessment
Lower bound	9	6	RDF 6-3 interval overlapped the KAc RDF interval and was therefore equivalent	9	8	RDF 6-12 interval overlapped the KAc RDF interval and was therefore equivalent
Mean	11	8		10	9	
Upper bound	12	10		11	10	

Table 13. Comparison of Anti-Icing Holdover Times

	HOT: Anti-Icing Series No. 1 (Confidence interval at RCR=9), min.			HOT: Anti-Icing Series No. 2 (Confidence interval at RCR = 9), min.		
Parameter	RDF 6-3	KAc RDF	Assessment	RDF 6-12	KAc RDF	Assessment
Lower bound	24	8	RDF 6-3 HOT interval overlapped the KAc RDF interval and was therefore equivalent	23	20	RDF 6-12 HOT interval overlapped the KAc RDF interval and was therefore equivalent
Mean	51	28		27	24	
Upper bound	78	47		31	27	

The results show that the Battelle fluids had comparable anti-icing friction and HOT performance compared to the commercial KAc RDF.

A comparison of deicing performance is provided in Table 14. The results show that the Battelle fluids had comparable deicing friction performance compared to the commercial KAc RDF.

Qualitative results included surveys to assess ease of use and ease of maintenance; see Table 15. The results indicate the Battelle-RDFs should have comparable performance in these areas.

Table 14. Comparison of Deicing Friction Values

Parameter	RCR: Deicing Series No. 1 (Confidence interval at 2.7 hours elapsed time)			RCR: Deicing Series No. 2 (Confidence interval results were found to be independent of elapsed time)		
	RDF 6-12	KAc RDF	Assessment	RDF 6-3	KAc RDF[(a)]	Assessment
Lower bound	5	4	RDF 6-12 interval overlapped the KAc RDF interval and was therefore equivalent	4	3	RDF 6-3 interval overlapped the KAc RDF interval and was therefore equivalent
Mean	5.4	4.8		6	9	
Upper bound	6	5		7	16	

(a) The broader range and the higher RCR figures obtained with the commercial RDF were unexpected based on the prior anti-icing and deicing test results. The high winds experienced after the ice was formed for this test may have resulted in uneven ice coverage with varying ice thicknesses.

Table 15. Results of Qualitative Evaluation Survey

Parameter	Mean Rating (1 to 10; 10 is best)		
	RDF 6-12	RDF 6-3	KAc RDF
Ease of Use	8.3	8.3	8.2
Ease of Maintenance	8.6	8.4	8.7

6.0 PERFORMANCE ASSESSMENT

A summary of the performance assessment was provided earlier in Table 3. In all cases, the Battelle-RDFs met the pre-established acceptance criteria. A brief review is provided below.

6.1 QUANTITATIVE DATA ANALYSIS

The anti-icing friction and HOT success criteria were met for both Battelle-RDFs because their intervals overlapped the KAc RDF intervals. This is shown graphically on Figures 3, 4, and 5.

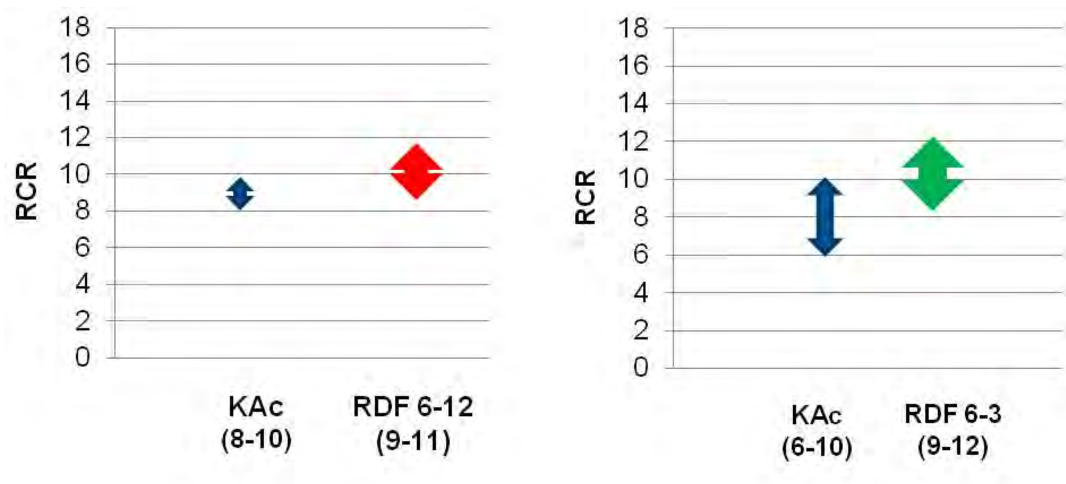

Figure 3. Comparison of Anti-Icing Friction Test Confidence Intervals for RDF 6-12 and RDF 6-3 versus KAc RDF

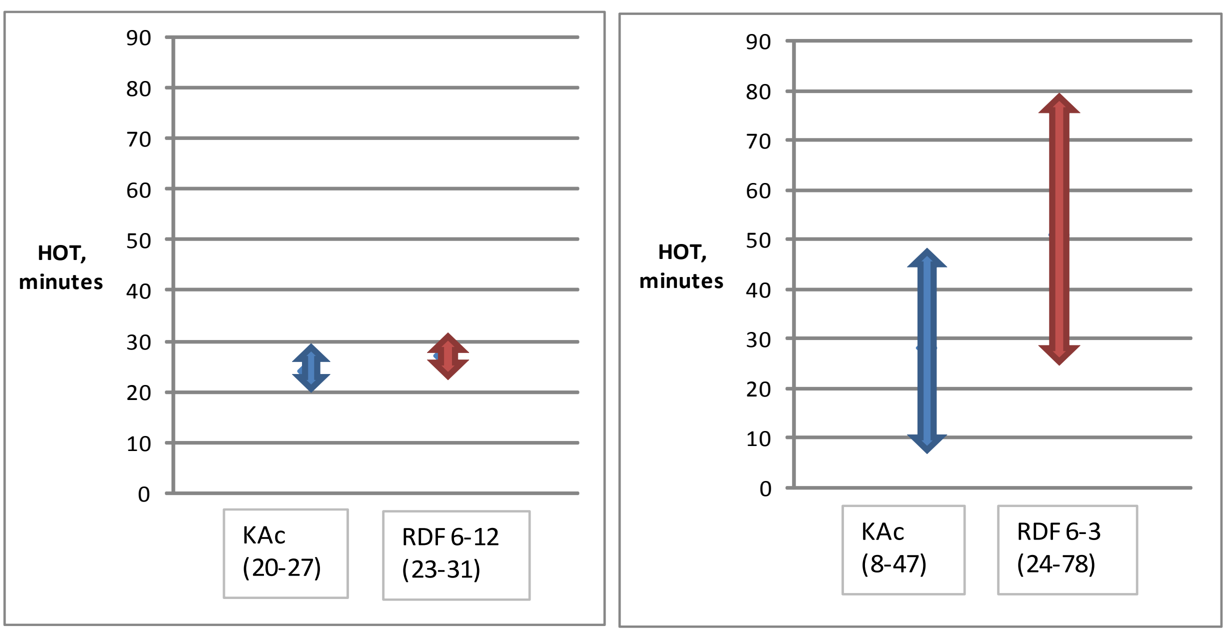

Figure 4. Comparison of Anti-Icing HOT Intervals for RDF 6-12 and RDF 6-3 versus KAc RDF

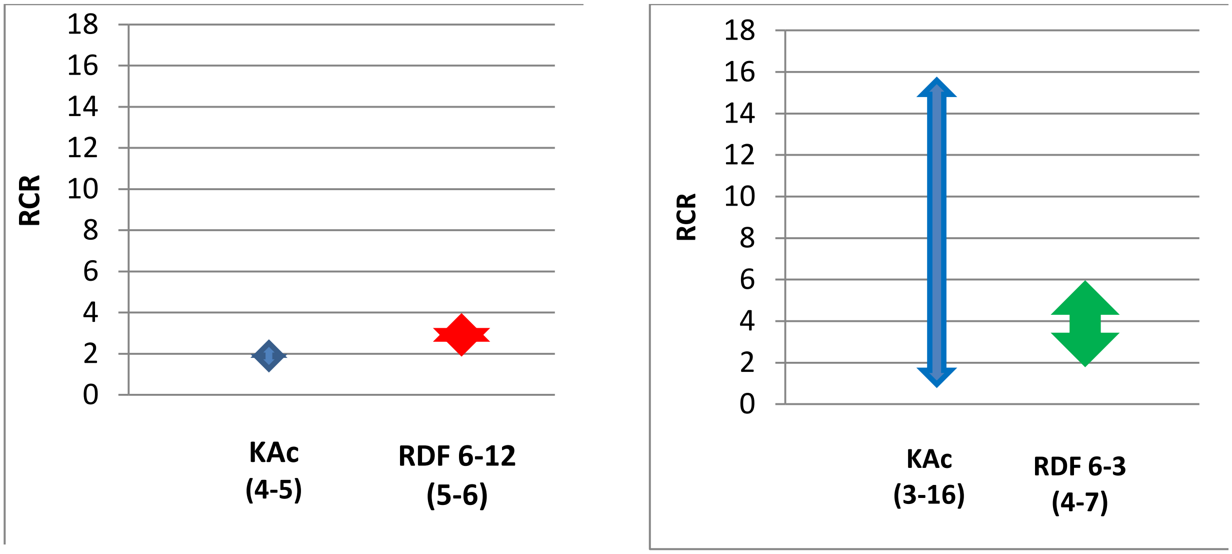

Figure 5. Comparison of Deicing Friction Test Confidence Intervals for RDF 6-12 and RDF 6-3 versus KAc RDF

6.2 QUALITATIVE DATA ANALYSIS

The ease of use and maintenance success criteria were met because the means were nearly identical to the KAc RDF ratings (and well within the ± 2 digit allowable bounds). This is shown graphically on Figure 6.

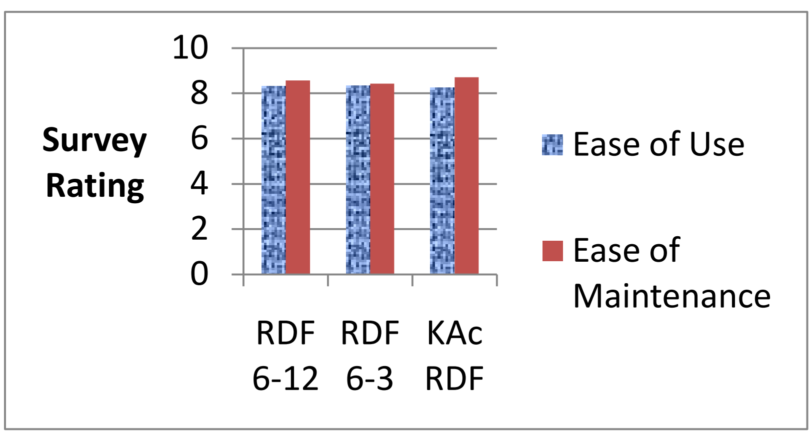

Figure 6. Relative Results from Ease of Use and Ease of Maintenance Surveys

7.0 COST ASSESSMENT

The development of a cost-effective RDF with superior environmental and material compatibility properties is critical to its acceptance at DoD and commercial airports. While the impact of excessive corrosion and degradation of aircraft materials on aircraft owners is substantial, the airport/runway operators (not the aircraft owners) pay for the fluids and, therefore, seek the lowest cost RDFs. An environmentally superior and less corrosive RDF at a higher cost may not be acceptable. Using the data gathered in this demonstration, a life-cycle analysis was conducted to determine if there was a benefit to using Battelle-RDFs.

Good numbers on RDF consumption data are difficult to obtain. There are 80 USAF sites, located in the northern half of the U. S. (including Alaska) where RDF would likely be used. These include 31 active USAF bases, 45 Air National Guard bases, and 4 Air Force Reserve Command bases [19]. AFCESA conducted a survey [20]. They solicited usage information and received the following responses for the 2009/2010 deicing season as noted in Table 16.

Table 16. Runway Deicing Fluid Usage Data Collected by Survey

Installation	RDF Usage, gal	Installation	RDF Usage, gal
Minot AFB, ND	3,300	WPAFB, OH[(a)]	14,200
Ellsworth AFB, SD	3,000	Eielson AFB, AK	4,035
Mountain Home AFB	3,450	Misawa, Japan	81,996
Hill AFB, UT	56,013	Osan, S. Korea	12,000
Elmendorf AFB, AK	105,000	Kunsan, S. Korea	24,000

(a) Obtained separately from personnel at WPAFB based on the 2008/2009 deicing season.

The total is ~307,000 (370k) gallons and represents only about 10% of the possible respondents. The average is ~31k gallons. No data were collected from the Air Force Reserve (AFR) or Air National Guard (ANG) bases, but their usage presumably would be lower. Assuming each of the 31 Air Force Bases located in the northern half of the US consumed the average per base usage (31k gallons), the annual usage would be 961k gallons per year (gpy). Assuming the AFR and ANG bases use ~1k gallons/year, the US Air Force usage would be ~1 million gpy.

For the purposes of this cost assessment, it was assumed that the average RDF usage for the entire DoD is ~1 million gallons/year. This seems consistent with the estimate the commercial sector consumes ~8 million gallons/year of liquid RDF in the U. S. [21].

Cost figures for the transition from KAc RDF to Battelle-RDF were estimated for the following three levels of changeover:

1. A single “typical” Air Force base: 31k gpy.
2. All DOD airfields: 1 million gpy.
3. All airports (military and civilian) in the U. S.: 9 million gpy.

7.1 COST MODEL

A description of the cost elements in the cost model are provided in Table 17.

Table 17. Cost Model for RDF Replacement

Cost Element	Data Collected During the Demonstration
Capital Costs	
Hardware capital costs	Estimates made based on the need to modify the RDF storage tank or spray truck (pumps, seal, nozzles, etc.)
Installation costs	Labor and materials to make any necessary modifications to the RDF fluid equipment
Operating Costs	
Consumables	Estimate based on the cost to procure raw material, formulate, and distribute the RDFs to the base, plus profit
Facility operating costs	Charge for the number of operators, fuel or equipment needed to deice the airfield, and wastewater treatment charges
Operator training	Estimate of operator training
Maintenance	Charge for required maintenance and the labor and materials for the maintenance actions

Provided on the next pages is more information on each cost element, including:

1. A brief description of the cost element.
2. A list of what data were collected and the basis for the cost estimate.
3. An explanation of how the data was interpreted and how other important issues were addressed.

7.1.1 Hardware Capital Costs

7.1.1.1 Description of Cost Element

This cost element covers hardware costs for fluid storage and spraying equipment modification.

7.1.1.2 Data to Be Collected and Basis for Estimate

The right to manufacture and distribute Battelle-RDFs was licensed to Basic Solution North America Corporation, a major supplier of KAc RDFs in North America and Europe. Basic Solutions began selling Battelle-RDF 6-4 under the trade name **GEN3 64™** for the 2009/2010 deicing season. (Formulation 6-4 is similar to the 6-12 and 6-3 formulations except has a higher bio-based content.) Fifteen Canadian commercial airports and four USA commercial concerns are using or testing **GEN3**. In all these commercial airport trials, **GEN3 64™** was used without modification to the storage tanks, transfer pumps, deicing fluid trailers, spray nozzles, or fluid delivery pumps. This supports the conclusion that Battelle-RDFs can be used as a drop in replacement.

7.1.1.3 Data Interpretation

No capital costs need be included for conversion from KAc RDF to Battelle-RDF 6-12 or 6-3. Thus, this cost element is zero.

7.1.2 Installation Costs

7.1.2.1 Description of Cost Element

This cost element includes required labor and materials to make necessary modifications to the RDF fluid equipment.

7.1.2.2 Data to Be Collected and Basis for Estimate

Because it was concluded the Battelle-RDF can be utilized as a drop-in replacement, no data needed to be collected.

7.1.2.3 Data Interpretation

Because no equipment installation or modification will be needed, this cost element is zero.

7.1.3 Consumables

7.1.3.1 Description of Cost Element

The costs cover the RDF raw-material costs, formulation charges, profit, and transportation charges associated with the delivering the RDF to the Air Force bases.

7.1.3.2 Data Collected and Basis for Estimate

The following unit cost data were collected for KAc, bio-based FPDs (crude and pure), PG, and additives through telephone contact with material suppliers in May 2010:

- KAc (50% solution): $0.33/lb (or > $0.66 on a 100% basis)
- Bio-based FPD (pure, 99.7% solution): $0.32/lb
- Bio-based FPD (crude, 69% solution): $0.11/lb (after purification for FFA and color removal)
- PG: $0.85/lb
- Additives: $2 to 4/lb depending on the process.

We assumed that the RDF would be manufactured in a toll facility. Based on an estimate from the toll producer, we used a formulation charge of $0.86/gal. Adding in profit at $1.00/gal and transportation charges of $0.17/gal (based on $0.16/ton-mile and a fixed distance of 200 miles from the formulation site to the user), the selling price was estimated as follows:

- Battelle-RDF 6-12: $4.96/gal
- Battelle-RDF 6-3: $5.51/gal
- KAc RDF: $5.82/gal
- KAc + PG RDF: $6.97/gal.

The consumables costs for the three scenarios are presented in Table 18.

Table 18. Estimated Consumable Costs by Scenario

Fluids (fluid price, $/gal)	Scenarios, $k/year		
	Single Base (31k gal RDF /year)	All DoD (1 million gal RDF /year)	All U.S. Airports (9 million gal RDF/year)
Consumables			
Battelle-RDF 6-12 (4.96)	154	4,956	44,602
Battelle-RDF 6-3 (5.51)	171	5,509	49,584
KAc RDF (5.82)	181	5,823	52,405
KAc + PG RDF (6.97)	216	6,965	62,688

7.1.3.3 Data Interpretation

The interpretation is that consumable costs can be significantly lowered by switching to Battelle-RDFs. For example, for if the DoD were to switch from KAc RDF to Battelle-RDF 6-12, it would allow a savings of approximately ~$0.9 million/year.

7.1.4 Facility Operating Costs

7.1.4.1 Description of Cost Element

Facility operating costs include the labor cost for the operators, fuel for equipment needed to deice the airfield, maintenance of fluid application equipment, upkeep of the runway surfaces, plus wastewater disposal charges.

7.1.4.2 Data Collected and Basis for Estimate

No additional labor, fuel, or equipment and runway maintenance needs were identified based on the findings from the ease of use and maintenance surveys and commercial experience with **GEN3**. Therefore the only difference in operating costs will be the BOD surcharge. This surcharge was based on the BOD content of the various RDFs. An oxidative load surcharge of ~$0.05/lb BOD is typical based on the experience at commercial airports. The wastewater-treatment cost calculations for the three scenarios are presented in Table 19.

Table 19. Wastewater Treatment Costs by Scenario

Fluids (lb BOD/lb fluid) [lb fluid/gal fluid]	Wastewater Treatment Costs by Scenario, $k/year [(a)]		
	Single Base (31k gal RDF/year)	All DoD (1 million gal RDF/year)	All U.S. Airports (9 million gal RDF/year)
Battelle-RDF 6-12 (0.26) [10.43]	4	136	1,221
Battelle-RDF 6-3 (0.3) [10.48]	5	157	1,415
KAc RDF (0.15) [10.71]	2	80	723
KAc + PG RDF (0.37) [9.66]	6	179	1,608

(a) Basis: BOD surcharge = $0.05/lb BOD.

In the example above, the BOD surcharge for a single AFB was compared for Battelle-RDF 6-12 versus KAc RDF:

> (31,000 gal RDF 6-12/year) * (10.43 lb/gal RDF of Battelle-RDF 6-12) * (0.26 lb BOD/lb RDF 6-12) * ($0.05/lb BOD) = $4k/year.
>
> (31,000 gal KAc RDF/year) * (10.71 lb/gal RDF of KAc RDF) * (0.15 lb BOD/lb KAc RDF) * ($0.05/lb BOD) = $2k/year.

The difference is about $2k/year per base, or ~1% of the annual RDF-purchase expense per base.

7.1.4.3 Data Interpretation

The estimated charge to facility operating costs due to the slightly higher BOD of the Battelle-RDFs (compared to the KAc RDF) has a very minor impact on total costs.

7.1.5 Training Costs

7.1.5.1 Description of Cost Element

This cost element includes required training to instruct operators in the differences in utilizing Battelle-RDF versus the standard KAc RDF.

7.1.5.2 Data to Be Collected and Basis for Estimate

Because it was concluded the Battelle-RDF can be utilized as a drop-in replacement, there would be little or no training required.

7.1.5.3 Data Interpretation

Because no training or operational modification will be needed, this cost element is zero.

7.1.6 Maintenance of Aircraft

7.1.6.1 Description of Cost Element

For this evaluation, maintenance costs will be limited to the deterioration of carbon-carbon brake pad assemblies in aircraft and Cd-plated electrical connectors and airfield lighting.

7.1.6.2 Data Collected and Basis for Estimate

The most significant factor, in terms of costs, is the aggressive attack of KAc-RDF on carbon brakes (due to catalytic oxidation). According to a briefing at the SAE G-12 “Carbon Pad Corrosion Working Group,” [22], RDF-related carbon-carbon corrosion costs are around $3 to 5 million per year per major civilian airline. No cost figures are available for the USAF but costs are significant. For instance, the cost to replace the carbon-carbon brake system for a single C-

17 is estimated at $400k per set (not including labor) [23]. For cost estimating purposes it was assumed that the entire USAF fleet had brake corrosion costs similar to a major airline (i.e., $3 to 5 million/year). The carbon-pad corrosion costs for a single base were estimated at 1/31th of the full-fleet cost (since there are 31 USAF bases in the northern half of the U. S.), or ~$100k/year. To estimate the annual carbon-pad corrosion costs for all U. S. airports ($30 million), the number of U. S. airlines was multiplied times the per-airline RDF-induced carbon-carbon corrosion costs. It was assumed there were 10 major airlines including the USAF; i.e., American Airlines, Cargo (DHL, FedEx, UPS), Continental Airlines, Delta Airlines, Northwest Airlines, Southwest Airlines, United Airlines, US Airlines, and minor carriers (Jet Blue, Frontier, Alaska Airlines), plus the USAF. Therefore the annual costs was $3 million/airline times 10 airlines, or $30 million/year.

Based on the corrosion rates in Table 12, the following corrosion-level multiplier was established for the Battelle-RDFs and KAc RDF:

- KAc RDF: Standard, 100% of carbon-carbon corrosion costs
- Battelle-RDF 6-12: 61% reduction [base on (18% weight loss – 7%)/18%]
- Battelle-RDF 6-3: 78% reduction [(18% - 4%)/18%].

The calculated cost for carbon-carbon corrosion is noted in Table 20.

Table 20. Estimated RDF-Induced Carbon-Carbon Brake Corrosion Costs by Scenario

Fluids (Corrosion Reduction Compared to KAc RDF)	Carbon-Carbon Corrosion Costs, $k/year $k/year		
	Single Base (1/31 of Airline)	All DoD (1 airline)	All U.S. Airports (10 airlines)
Battelle-RDF 6-12 (61 percent)	38	1,170	11,700
Battelle-RDF 6-3 (78 percent)	21	660	6,600
KAc RDF (0 percent)	97	3,000	30,000

The second key maintenance concern is the RDF-induced corrosion of Cd-plated electrical connectors and airport lighting systems. While many have indicated these costs represent a significant maintenance costs, there are no published estimates of the dollar amount associated with the damage. Therefore it was assumed to be 10% of the annual carbon-carbon brake pad cost; i.e., 10% * $3 million/year/airline = $0.3 million/year/airline.

Based on the corrosion rates in Table 11, the following corrosion-level multiplier was established for the Battelle-RDFs and KAc RDF:

- KAc RDF: Standard, 100% of Cd corrosion costs
- Battelle-RDF 6-12: 81% reduction [81% calculated as: (0.16 mg/cm^2/24 hours - 0.03 mg/cm^2/24 hours)/0.16 mg/cm^2/24 hours]
- Battelle-RDF 6-3: 75% reduction [(0.16-0.04)/0.16]

The calculated cost for Cd corrosion is noted in Table 21.

Table 21. Estimated RDF-Induced Cadmium Corrosion Costs by Scenario

Fluids (Corrosion Reduction Compared to KAc RDF)	Cadmium Corrosion Costs, $k/year $k/year		
	Single Base (1/31 of airline)	All DoD (1 airline)	All U.S. Airports (10 airlines)
Battelle-RDF 6-12 (81 percent)	2	57	570
Battelle-RDF 6-3 (75 percent)	2	75	750
KAc RDF (0 percent)	10	300	3,000

7.1.6.3 Data Interpretation

The potential saving from reduced carbon-carbon brake and Cd corrosion are significant. For example, combining Battelle-RDF 6-12 versus KAc RDF costs in Table 20 and 21, the annual savings for a single base, the USAF, and the all U. S. airports, are $67 k, $2.1 million, and $21 million, respectively.

7.2 COST DRIVERS

Based on the analysis covered in Section 7.1, the major cost drivers are fluid cost and carbon-carbon corrosion costs. The cost impact of the higher oxygen demand of the Battelle-RDFs and Cd-corrosion costs is so low, that it is insignificant.

7.3 COST ANALYSIS AND COMPARISON

To assess the relative attractiveness of switching away from conventional KAc RDF, three scenarios were considered. Capital costs for the switch were essentially zero, so the cost analysis focused on the impact on annual costs.

7.3.1 Base Case Description

The base case is for a "typical" USAF base located in the mid-to-northern section of the U. S. Two alternative cases were also considered, where the entire USAF and the rest of the DoD switched to a Battelle-RDF, and where all U. S. airports (military and civilian) switched to this bio-based, low-corrosion alternative RDF.

7.3.2 List of Assumptions

The following four assumptions were made to support the cost analysis and comparison of the Battelle-RDFs versus conventional KAc RDF:

1. Based on WPAFB's RDF usage, it was assumed that a typical installation would consume ~31,000 gallons of RDF each year.
2. Based on the estimate that the DoD consumes approximately 1 million gallons of RDF a year, there are ~31 "typical" U. S. military users of RDF.
3. Since RDF-induced corrosion cost estimates are only available on a "per airline" basis, it was assumed that the USAF/DoD together would represent one airline.
4. Recognizing that the relative costs of RDF components change with time, it was assumed that the price movement would be relatively small and that PG would always be more expensive than

KAc, which would always be more expensive that purified bio-based materials, which would be more expensive than crude bio-based materials (even after upgrading to remove FFA and color and odor bodies).

7.3.3 Approach to Developing the Estimated Life-Cycle Cost

Life-cycle costs (LCC) are the sum of the costs to acquire RDF components, formulate and distribute the RDF to the users, the cost to apply, and the cost to remediate any adverse environmental effect from cradle to grave. If modifications to the standard equipment or procedures need to be instituted, then the capital cost to make the modifications and to re-train the users should be included on an amortized basis.

The demonstration at WPAFB, and full-scale implementation of similar bio-based RDFs at over 19 commercial airports in Canada and the U. S., indicated that the Battelle-RDF can serve as a drop in replacement with similar ease of use, ease of maintenance, and anti-icing and deicing performance. Therefore, there are no capital costs or training cost impacts.

Therefore, the estimated operating cost for the Battelle-RDFs and commercial KAc RDF can serve as a valid LCC cost estimate of these fluids.

7.3.4 Cost Comparison

The costs components for the various fluids, described in Section 7.1, were combined to provide an estimate of the operating costs of each fluid for each of the three scenarios; see Table 22.

7.3.5 Cost Analysis Findings

Analysis of the projected non-labor operating costs indicates that the most significant cost factor is the cost of the RDF fluid. Carbon-carbon brake pad corrosion is also a significant contributor, while Cd corrosion- and wastewater-treatment costs are minor contributors.

Table 22. Estimate of Changes in the Non-Labor Operating Costs, by Scenario

Cost Components	Operating Costs, by Scenario $k/year		
	Single Base	All DoD	All U.S. Airports
Battelle-RDF 6-12			
Consumables	154	4,956	44,602
Wastewater treatment	4	136	1,221
Cd corrosion	2	57	570
Carbon-carbon brake corrosion	38	1,170	11,700
Total	197	6,318	58,092
Battelle-RDF 6-3			
Consumables	171	5,509	49,584
Wastewater treatment	5	157	1,415
Cd corrosion	2	75	750
Carbon-carbon brake corrosion	21	660	6,600
Total	199	6,402	58,349
KAc RDF			
Consumables	181	5,823	52,405
Wastewater treatment	2	80	723
Cd corrosion	10	300	3,000
Carbon-carbon brake corrosion	97	3,000	30,000
Total	289	9,203	86,128

As expected, savings increase as the scale of operations increase. But even on a single base level, the potential savings of $92k/year for switching to Battelle-RDF 6-12 (and $90k/year for switching to Battelle-RDF 6-3) from KAc RDF are noticeable.

The annual savings, by scenario and Battelle-RDF type, are shown in Figure 7. Note: The numbers above the blue bars in Figure 7 indicate the annual savings for switching to RDF 6-12 from KAc RDF. As noted by the relative size of the blue and red bars, the savings for switching to RDF 6-3 are very similar.

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8.0 IMPLEMENTATION ISSUES

8.1 POTENTIAL REGULATIONS AFFECTING IMPLEMENTATION

Currently, KAc RDFs can meet the CWA requirements. While the EPA has proposed new airport discharge requirements, they include only a ban on the use of urea for runway deicing (which the USAF adopted years ago). Current regulations do not require the use of bio-based RDFs to meet discharge requirements. However, there likely will be pressure on the airport authorities in the future to control the toxicity of RDFs and such pressure could encourage the use of bio-based RDFs or KAc+PG RDFs.

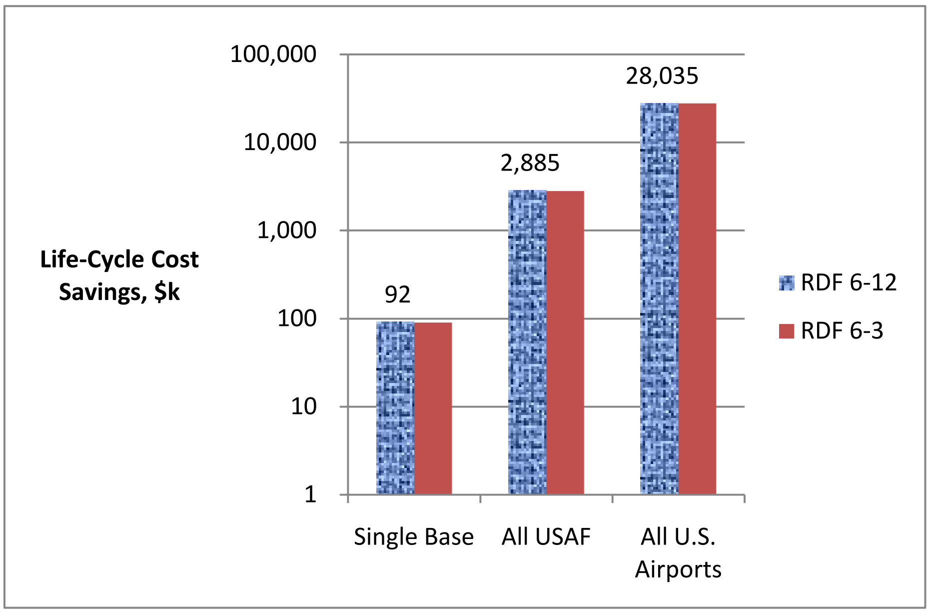

Figure 7. Comparison of Projected Savings by Scenario and RDF Type

Three Presidential EOs promote increased use of bio-based materials. So far, these orders have not had a significant impact on bio-based materials demand, and alone will not ensure the implementation of Battelle-RDFs.

8.2 END USER CONCERNS, RESERVATIONS, AND DECISION-MAKING FACTORS

Users may express concern because the fluid is new and they may have reservations because of its potential damage to aircraft or weapon system components. Reservations should be allayed once the range of tests performed and the consistent equal-or-better corrosion properties of Battelle-RDF are disseminated.

8.3 RELEVANT PROCUREMENT ISSUES

On 18 January 2011, we received an email from Dr. Craig A Rutland of AFCESA indicating that the fluid had been reviewed and approved for use on Air Force airfields, as required for Air Force use. A copy of his email is provided below:

From: Rutland, Craig A Civ USAF AFCESA AFCESA/CEOA
[mailto:Craig.Rutland@tyndall.af.mil]
Sent: Tuesday, January 18, 2011 5:48 PM
To: Wyderski, Mary T Civ USAF AFMC ASC/WWME
Cc: Benedyk, Preston J Civ USAF AFCESA AFCESA/CEOO; ISAACS, LARRY K GS-14 USAF DoD AFCEE/TDNQ; Fetter, Clifford C Civ USAF AFCESA AFCESA/CEOA; Benedyk, Preston J Civ USAF AFCESA AFCESA/CEOO
Subject: RE: Battelle Runway Decing Fluid

Ma'am

I apologize for the delay. I just spoke with Dr Isaacs and I believe we are in agreement.

We believe the Battelle deicing fluids 6-4, 6-3, and 6-12 formulations will not harm the runway surfaces, asphalt or concrete. The BOD of these formulations is slightly higher than the currently used products. Therefore, the use of the product on specific airfields may be limited by existing permits and storm water quality laws and regulations.

Our analysis did not consider the effects of these fluid on the aircraft.
Prior to general use of this product it is recommended that AFMC and the individual aircraft SPOs examine the effect of these fluid on corrosion, brake operation, sensors, coatings, connectors and weapon systems.

Please let me know if you require additional information

V/R
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The implementation path for new deicing materials in the USAF (and DoD) is evolving. The path is outlined in AFI 32-1002; see relevant excerpts for the AFI in Figure 8.

2.1.8 Weapon System Single Managers (WSSMs) including Aircraft Single Managers (ASMs) Responsibilities

2.1.8.1. Evaluate impact of desired/requested airfield deicing/anti-icing agents on systems' performance for which they are responsible.

2.1.8.2. Identify to MAJCOMs the funding needs associated with the analysis and testing required to evaluate the impact of desired/requested airfield deicing/anti-icing agents.

2.1.9 Aircraft Single Manager (ASM) Responsibilities

2.1.9.1. Upon receipt of a MAJCOM request for approval to use an airfield deicing/anti-icing agent, the ASMs will become the focal point for coordination. They will act as single interface to the MAJCOM and coordinate the approval and/or requirements for all other weapon system components used on the aircraft to include those components managed by different Single Managers (e.g., landing gear, electronic countermeasure pods, navigational pods, weapons).

2.1.9.2. Upon notification from a MAJCOM of airfield deicing/anti-icing agents being used at a non-Air Force owned installation, ASMs will:

2.1.9.2.1. Advise any Weapon System Single Managers whose components are used on their aircraft of the airfield deicing/anti-icing agents being used.

2.1.9.2.2. Work with the respective Weapon System Single Managers to adjust maintenance activities and/or inspection intervals, or impose operational restrictions to mitigate if possible, any impact of the airfield deicing anti-icing agents.

Figure 8. Implementation Procedures Outlined in AFI 32-1002

While the AFI describes the roles of the WSSM and the ASM, it does not supply a set of clear step-by-step procedures to follow for new fluid implementation. Based on discussion with AF user, procurement experts, deicing experts, and the AFCESA, the following three steps must be completed before any new deicing fluid can be procured and utilized by DoD airfields:

1. **Data collection.** An advocate in the Weapon System organization in a MAJCOM (e.g., Mary Wyderski acting for the Weapon System) must:
    a. Collect data to ensure the fluid is suitable for USAF and DoD needs. [Completed] For RDF, this includes documentation to show the fluid complies with:
        i. AMS 1435A
        ii. Joint Test Protocol (in our case, the MTMS)
        iii. Performance requirements (in our case, the data in the SERDP report and the ESTCP demo)
    b. Present the data to AFCESA for review [Completed]

c. Obtain approved by the AFCESA, that he fluid will be approved for use general use [Completed]
    i. As the AFI is not updated annually (it was last updated October 1999), it is unlikely the AFI would be modified to include the use of a single additional RDF.
    ii. Instead, AFCESA would issue a memo to the MAJCOMs informing them of the inclusion of the new approved RDF.
    iii. It would be the responsibility of the MAJCOMs to convey the information to the ASM/WSSM for approval on their specific aircraft of weapon system.

d. Present the data package to the ASMs/WSSMs and obtain their approval for the bio-based RDFs use on their aircraft/weapon system.

2. **Obtain a National Stock Number (NSN)**. The new fluid may be assigned a NSN to facilitate the procurement of **GEN3** (this is not required, but may prove useful). These NSNs are managed and assigned by the Defense Logistics Information Service in Battle Creek, Michigan [24]. Manufacturers and suppliers do not have the authority to request a NSN. This is usually accomplished once a requirement/need for that manufacturer's/supplier's item has been identified by a military service, NATO country or federal/civil agency (e.g., Mary Wyderski acting for the Air Force). Information collected during the assignment of the NSNs includes qualified vendors, unit pricing information, and quality requirements (such as compliance with AMS 1435A).

3. **Disseminate information/AFI changes to other WSSMs and ASMs.** The ASM designee (such as Mary Wyderski), may present the RDF suitability findings and changes in the AFI to other WSSMs and ASMs. This could be one on one or at a national logistics meeting/conference. The WSSMs and ASMs can then accept the changes and allow this new fluid to be used on their weapon system or aircraft. In some cases, special material-compatibility concerns may delay acceptance; or additional material-specific testing may be required by a weapon system before acceptance.

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APPENDIX A: POINTS OF CONTACT

The points of contact are noted in Table A-1.

Table A-1. Points of Contact

Point Of Contact Name	Organization Name Address	Phone E-mail	Role in Project
Mary Wyderski	AF/ASC WPAFB OH	937-656-5570 office 937-304-3833 cell mary.wyderski@wpafb.af.mil	Principal Investigator
William Kassinos	AF/88 Air Base Wing WPAFB OH	(937) 257-6207 william.kassinos@wpafb.af.mil	Airfield supervisor
Michael Patterson	AF/88 Air Base Wing WPAFB OH	(937) 904-2390 michael.patterson3@wpafb.af.mil	Fluids application supervisor
James Tufano	AF/88 Air Base Wing WPAFB OH	(937) 904-2056 james.tufano@wpafb.af.mil	Fluids applications supervisor
Romulo Alcantara	AF/88 OSS/OSAM WPAFB OH	(937) 257-2131 romulo.alcantara@wpafb.af.mil	Airfield supervisor
Brian Robinson	AFMC 88 ABW/CEMEP WPAFB OH	(937) 257-7360 brian.robinson@wpafb.af.mil	Fluids applier
Elizabeth Berman	AF/AFRL WPAFB OH	937-656-5700 office elizabeth.berman@wpafb.af.mil	Specialized DoD-materials expert
Michael Sanders	HQ AFPET/PTPT	(937) 255-8107 michael.sanders@wpafb.af.mil	AF deicing expert
Benet Curtis	HQ AFPET/PTPT	(937) 255-8039 benet.curtis@wpafb.af.mil	AF deicing expert
Karen Beason	AF/88 Air Base Wing/CEVO	937-257-5899 Karen.Beason@wpafb.af.mil	Supported review and approval of AF Form 813
Charles Ryerson	Army/ CRREL Hanover, NH	603-646-4487 office charles.c.ryerson@usace.army.mil	Army deicing expert
Don Tarazano	SAIC Dayton, OH	937-431-2242 office donald.tarazano@wpafb.af.mil	Airfield test support
James Davila	SAIC Dayton, OH	937-431-2272 office james.a.davila@saic.com	SAIC Program Manager
Preston Benedyk	AFCESA/CEOO Tyndall AFB	(850) 283-6582 preston.benedyk@tyndall.af.mil	AFCESA observer
Nick Conkle	Battelle Columbus, OH	614-937-4171 cell 614-424-5616 office conkle@battelle.org	Airfield testing director
Satya Chauhan	Battelle Columbus, OH	614-937-0851 cell 614-424-4812 office chauhan@battelle.org	RDF expert
Kelvin Williamson	Basic Solutions Toronto, Canada	905-562-0770 kelvin@basic-solutions.ca	RDF vendor and deicing expert

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